Interoception and Mental Health: A Roadmap

Supplemental Information

Feature	Definition	Paradigms
Attention	Observing internal body sensations	C, GI (Simmons et al., 2013) R (Farb et al., 2013)
Detection	Presence or absence of conscious report	C (Khalsa et al., 2008) C (Garfinkel et al., 2013) R (Davenport et al., 2007) R (Paulus et al., 2012) GI (Holzl et al., 1996)
Magnitude	Perceived intensity	C, R (Khalsa et al., 2009b) R (Davenport et al., 2007) GI (Herbert et al, 2012b) GI (Naliboff et al., 2006) U (Jarrahi et al., 2015)
Discrimination	Localize sensation to a specific channel or organ system, and differentiate it from other sensations	C, R (Khalsa et al., 2015) GI (Aziz et al., 2000)
Accuracy (sensitivity)	Correct and precise monitoring	C (Schandry et al., 1993) C, R (Khalsa et al., 2009a) R (Daubenmier et al., 2013) GI (Zaman et al., 2016)
Insight	Metacognitive evaluation of experience/performance (e.g., confidence-accuracy correspondence)	(Khalsa et al., 2008) (Garfinkel et al., 2015)
Sensibility	Self-perceived tendency to focus on interoceptive stimuli. Trait measure.	(Garfinkel et al., 2015) (Garfinkel et al., 2016)
Self-report scales	Psychometric assessment via questionnaire. State/trait measure.	(Shields et al., 1989) (Porges, 1993) (Labus et al., 2007) (Mehling et al., 2012)

Supplementary Table S1. Features of interoceptive awareness. The illustrated paradigms span several physiological systems including the cardiac (C), respiratory (R), gastrointestinal (GI), and urinary (U) systems. Note that the paradigms and references listed here are not exhaustive; they are provided as illustrative examples. Many other approaches and paradigms exist, some of which are described in the main manuscript.

Interoception taxonomy

Interoception: The overall process of how the nervous system senses, integrates, stores, and represents information about the state of the inner body at conscious and unconscious levels. It is important to note that the contemporary definition of interoception is not synonymous with the term viscероception, but it does subsume it. Viscероception classically refers to the perception of bodily signals arising specifically from visceral organs such as the heart, lungs, stomach, intestines, and bladder, along with other internal organs in the trunk of the body (1). Viscероception does not include organs like the skin or skeletal muscle, whereas interoception encompasses both visceral signaling and more broadly relates to all physiological tissues that relay a signal to the central nervous system about the current state of the body, including the skin and skeletal/smooth muscle fibers, via lamina I spinothalamic afferents (2-4).

Interoceptive awareness: Conceptualizations of interoceptive awareness have been rather diverse. The term was originally introduced in 1983 by Garner and colleagues (5), via the development of the 'interoceptive awareness' subscale, part of a self-report measure intended to assess eating disorder symptom severity. The items on the subscale were derived based on the clinicians' experience, as well as prior empirical work on 'gastric perceptivity' in eating disorders (6). However, only 2 of the 10 items actually assessed interoception-related symptoms ("I get confused as to whether or not I am hungry" and "I feel bloated after eating a small meal"), with the remainder of the subscale preferentially measuring alexithymia (e.g., "I get confused about what emotion I am feeling"). Ensuing publications over the next 20 years referred to interoceptive awareness in this context (1983-2004, a total of 51 in PubMed). Following a report by Critchley

et al. (2004) entitled “Neural systems supporting interoceptive awareness” (7), it has subsequently been used to encompass any (or all) of the different interoception features accessible to conscious self-report (2004-present, 288 publications in PubMed) (8). A more coherent and precise terminology has now been developed to describe its various components (Supplementary Table S1).

Interoceptive attention: The ability to direct attentional resources towards the source of internal body sensations. It can be captured (i.e., triggered involuntarily) in a stimulus dependent or ‘bottom up’ manner (9, 10), or shifted purposefully in a goal directed or ‘top down’ manner (11, 12). There is an important distinction about attentional ‘styles’, which may be viewed on a spectrum of anxiety driven, evaluative/avoidant on one extreme, to mindful, non-judgmental, and accepting on the other (13). The latter style tends to be cultivated during clinical applications of mindfulness and other forms of meditative practice.

Interoceptive detection: The ability to detect the presence or absence of a stimulus. It is a binary variable, similar to detection of a light source when it is switched on or off, or a judgment about whether a river is flowing or not.

Interoceptive magnitude: The intensity with which an internal bodily event is perceived. It is therefore a stimulus parameter reflecting the amount of signal. It is a continuous variable, e.g., reflecting how much dyspnea is present, and is typically gauged via subjective reports from the individual using rating scales, for example visual analogue scales and numerical rating scales. Magnitude estimation has been explained as a combination of prior expectations and current

sensory input (14), emphasizing its relevance for Hierarchical Bayesian Models (HBMs) of interoception. It is difficult to measure changes in this feature in the absence of physiological perturbations (15).

Interoceptive discrimination: An individual's ability to localize sensation within a specific interoceptive system and to differentiate it from non-interoceptive sensations. It often requires the ability to locate sensations to specific regions within the body (as opposed to elsewhere inside the body), or relative to an external signal. Examples include the ability to distinguish a feeling of fullness after a meal from an irritating cough, or from the noise of a television in the background. It may also require the ability to separate different sensations from within the same interoceptive source, for example, as occurs when swallowing a food bolus (proximal vs. distal esophageal sensation and subsequent gastric deposition).

Interoceptive accuracy: The ability to precisely and correctly monitor changes in internal body state. It is synonymous with interoceptive sensitivity, and it has been the most commonly studied feature of interoception. Typical approaches involve the simultaneous measurement of an objective marker (e.g., heart rate, degree of inspiratory breathing load), the subjective experience of the individual (e.g., counted heart rate, detection or intensity of breathing difficulty), and subsequent calculation of the relationship between them. Subjective variables may be dichotomous (e.g., sensation present or absent, as in interoceptive detection) or continuous (e.g. how intense the stimulus is, as in interoceptive magnitude or discrimination). The interoceptive stimuli that are attended to may be acutely punctuated (as in the heartbeat) or continuous and prolonged (as in gut or bladder fullness). Interoceptive accuracy necessarily depends upon interoceptive attention given

the reliance on attentional mechanisms for generating accuracy estimates. Common measurement examples include: 1) d' for heartbeat detection tasks (a signal detection metric (16, 17), cardiac error score for heartbeat counting tasks (18, 19), 2) cross correlations between heart rate and dial tracings of perceived intensity following adrenergic infusion (8, 20), 3) percent accuracy for detection of breathing occlusion (21), 4) intraclass correlations between bladder volumes and urinary urge (22), and 5) cross correlations between respiratory trace and slider tracings of the perceived phase and depth of respiration (23).

Interoceptive insight: The metacognitive measure detailing the correspondence between subjective experience and behavior. This is most typically evaluated by assessing the correspondence between accuracy and performance confidence on specific tasks. For example, in a study in which experienced meditators did not have different interoceptive accuracy on a heartbeat detection task, they exhibited differences in interoceptive self-report, reporting that the task was easier and their performance was improved relative to nonmeditators (24). In another study, performance on a heartbeat counting task was positively correlated with self-reported confidence estimates only in individuals with high but not low interoceptive accuracy scores (25) (note that replacement of the term 'interoceptive awareness' with 'interoceptive insight' in the prior study (25) is in keeping with the more coherent nomenclature suggested in this consensus statement).

Interoceptive sensibility: The self-perceived dispositional tendency to focus on interoceptive stimuli across daily life. Assessments of this trait measure inherently require an evaluation of self-perceived tendencies across broad time spans. This is commonly assessed by asking individuals to

reflect on their autobiographical experience by answering questions such as ‘To what extent do you believe you focus on and detect internal bodily sensations?’ (25, 26). Mehling (13) has argued that the measurement of interoceptive sensibility is substantially more complex than the approach employed by Garfinkel et al. (25), particularly as the rating does not capture the regulatory and accepting/non-judgmental aspects of experience that are relevant for clinical settings. To address this complexity Mehling (13) developed the Multidimensional Assessment of Interoceptive Awareness (MAIA), which assesses 8-items via self-report (Noticing, Not-Distracting, Not-Worrying, Attention Regulation, Emotional Awareness, Self-Regulation, Body Listening, and Trusting) (see next section).

Interoceptive self-report scales: The ability to reflect upon one’s autobiographical experiences of interoceptive states, make judgments about their outcomes, and describe them through verbal or motor responses. It is most commonly assessed experimentally using instruments or scales and there are a variety of them (25, 27-30). There are likely to be many constructs that can be identified within this level. For example, it may be possible to investigate dissociations between an individual’s self-report of their interoceptive experiences versus their partner report (e.g., someone who knows the participant well and has had regular opportunities to interact with and observe them in a variety of situations, an approach that has been utilized for neurological samples (31)). Accordingly, the self-report component may be viewed as one of the most complex and nuanced features awaiting further investigation.

Supplementary References

1. Janig W (1996): Neurobiology of visceral afferent neurons: neuroanatomy, functions, organ regulations and sensations. *Biol Psychol*. 42:29-51.
2. Cameron OG (2001): Interoception: The inside story - A model for psychosomatic processes. *Psychosomatic Medicine*. 63:697-710.
3. Olausson H, Lamarre Y, Backlund H, Morin C, Wallin BG, Starck G, et al. (2002): Unmyelinated tactile afferents signal touch and project to insular cortex. *Nat Neurosci*. 5:900-904.
4. Craig AD (2002): How do you feel? Interoception: the sense of the physiological condition of the body. *Nat Rev Neurosci*. 3:655-666.
5. Garner DM, Olmstead MP, Polivy J (1983): Development and validation of a multidimensional eating disorder inventory for anorexia-nervosa and bulimiaA. *International Journal of Eating Disorders*. 2:15-34.
6. Coddington RD, Bruch H (1970): Gastric perceptivity in normal, obese and schizophrenic subjects. *Psychosomatics: Journal of Consultation and Liaison Psychiatry*. 11:571-579.
7. Critchley HD, Wiens S, Rotshtein P, Ohman A, Dolan RJ (2004): Neural systems supporting interoceptive awareness. *Nat Neurosci*. 7:189-195.
8. Khalsa SS, Craske MG, Li W, Vangala S, Strober M, Feusner JD (2015): Altered interoceptive awareness in anorexia nervosa: Effects of meal anticipation, consumption and bodily arousal. *The International journal of eating disorders*. 48:889-897.
9. Hassanpour MS, Simmons WK, Feinstein JS, Luo Q, Lapidus R, Bodurka J, et al. (2017): The Insular Cortex Dynamically Maps Changes in Cardiorespiratory Interoception. *Neuropsychopharmacology*.
10. von Leupoldt A, Sommer T, Kegat S, Baumann HJ, Klose H, Dahme B, et al. (2009): Dyspnea and pain share emotion-related brain network. *NeuroImage*. 48:200-206.
11. Simmons WK, Avery JA, Barcalow JC, Bodurka J, Drevets WC, Bellgowan P (2013): Keeping the body in mind: Insula functional organization and functional connectivity integrate interoceptive, exteroceptive, and emotional awareness. *Human Brain Mapping*. 34:2944-2958.
12. Farb NA, Segal ZV, Anderson AK (2013): Attentional modulation of primary interoceptive and exteroceptive cortices. *Cereb Cortex*. 23:114-126. doi: 110.1093/cercor/bhr1385. Epub 2012 Jan 1019.
13. Mehling W (2016): Differentiating attention styles and regulatory aspects of self-reported interoceptive sensibility. *Philos Trans R Soc Lond B Biol Sci*. 371.
14. Petzschner FH, Glasauer S, Stephan KE (2015): A Bayesian perspective on magnitude estimation. *Trends Cogn Sci*. 19:285-293.
15. Khalsa SS, Lapidus RC (2016): Can Interoception Improve the Pragmatic Search for Biomarkers in Psychiatry? *Frontiers in psychiatry*. 7:121.

16. Brener J, Liu X, Ring C (1993): A method of constant stimuli for examining heartbeat detection: comparison with the Brener-Kluvitse and Whitehead methods. *Psychophysiology*. 30:657-665.

17. Khalsa SS, Rudrauf D, Tranel D (2009): Interoceptive awareness declines with age. *Psychophysiology*. 46:1130-1136.

18. Herbert BM, Ulbrich P, Schandry R (2007): Interoceptive sensitivity and physical effort: implications for the self-control of physical load in everyday life. *Psychophysiology*. 44:194-202.

19. Koch A, Pollatos O (2014): Cardiac sensitivity in children: sex differences and its relationship to parameters of emotional processing. *Psychophysiology*. 51:932-941.

20. Khalsa SS, Rudrauf D, Feinstein JS, Tranel D (2009): The pathways of interoceptive awareness. *Nat Neurosci*. 12:1494-1496.

21. Zhao W, Martin AD, Davenport PW (2003): Magnitude estimation of inspiratory resistive loads by double-lung transplant recipients. *1985)*. 94:576-582. Epub 2002 Oct 2011.

22. Heeringa R, van Koeveringe GA, Winkens B, van Kerrebroeck PE, de Wachter SG (2011): Degree of urge, perception of bladder fullness and bladder volume--how are they related? *J Urol*. 186:1352-1357. doi: 1310.1016/j.juro.2011.1305.1050.

23. Daubenmier J, Sze J, Kerr CE, Kemeny ME, Mehling W (2013): Follow your breath: respiratory interoceptive accuracy in experienced meditators. *Psychophysiology*. 50:777-789.

24. Khalsa SS, Rudrauf D, Damasio AR, Davidson RJ, Lutz A, Tranel D (2008): Interoceptive awareness in experienced meditators. *Psychophysiology*. 45:671-677.

25. Garfinkel SN, Seth AK, Barrett AB, Suzuki K, Critchley HD (2015): Knowing your own heart: distinguishing interoceptive accuracy from interoceptive awareness. *Biol Psychol*. 104:65-74.

26. Garfinkel SN, Tiley C, O'Keeffe S, Harrison NA, Seth AK, Critchley HD (2016): Discrepancies between dimensions of interoception in autism: Implications for emotion and anxiety. *Biol Psychol*. 114:117-126.

27. Labus JS, Mayer EA, Chang L, Bolus R, Naliboff BD (2007): The central role of gastrointestinal-specific anxiety in irritable bowel syndrome: further validation of the visceral sensitivity index. *Psychosom Med*. 69:89-98.

28. Shields S, M.E. M, A. S (1989): The body awareness questionnaire: reliability and validity. *J Pers Assess*. 53:802-815.

29. Porges S (1993): *Body perception questionnaire*. University of Maryland.

30. Mehling WE, Price C, Daubenmier JJ, Acree M, Bartmess E, Stewart A (2012): The Multidimensional Assessment of Interoceptive Awareness (MAIA). *PLoS One*. 7:e48230.

31. Barrash J, Asp E, Markon K, Manzel K, Anderson SW, Tranel D (2011): Dimensions of personality disturbance after focal brain damage: investigation with the Iowa Scales of Personality Change. *J Clin Exp Neuropsychol*. 33:833-852.

Interoception summit 2016 participant author appendix:

First Name	Last Name	Institution 1	Institution 2
Vivien	Ainley	Royal Holloway University	
Obada	Al Zoubi	University of Oklahoma	Laureate Institute for Brain Research
Robin	Aupperle	Laureate Institute for Brain Research	
Jason	Avery	Laureate Institute for Brain Research	
Leslie	Baxter	Barrow Neurological Institute	
Christoph	Benke	University of Greifswald	
Laura	Berner	University of California San Diego	
Jerzy	Bodurka	Laureate Institute for Brain Research	
Eric	Breese	Laureate Institute for Brain Research	
Tiffany	Brown	Unversity of California, San Diego	
Kaiping	Burrows	Laureate Institute for Brain Research	
Yoon-Hee	Cha	Laureate Institute for Brain Research	
Ashley	Clausen	Laureate Institute for Brain Research	
Kelly	Cosgrove	Laureate Institute for Brain Research	
Danielle	Deville	Laureate Institute for Brain Research	
Laramie	Duncan	Stanford University	
Patrice	Duquette	Patrice Duquette MDPC	
Hamed	Ekhtiari	Laureate Institute for Brain Research	
Thomas	Fine	University of Toledo	
Bart	Ford	Laureate Institute for Brain Research	
Indira	Garcia Cordero	Buenos Aires University	
Diamond	Gleghorn	Laureate Institute for Brain Research	
Yvette	Guereca	The University of Tulsa	
Mahlega	Hassanpour	Laureate Institute for Brain Research	
Tanja	Hechler	University of Trier	
Aaron	Heller	University of Miami	
Natalie	Hellman	The University of Tulsa	
Beate	Herbert	University of Teubingen	
Behnaz	Jarrahi	Stanford University School of Medicine	
Kara	Kerr	University of Tulsa	
Namik	Kirlic	Laureate Institute for Brain Research	
Megan	Klabunde	Stanford University	
Thomas	Kraynak	University of Pittsburgh	
Michael	Kriegsman	The University of Texas at Dallas	
Juliet	Kroll	Southern Methodist University	
Rayus	Kuplicki	Laureate Institute for Brain Research	

Rachel	Lapidus	Laureate Institute for Brain Research	
Trang	Le	University of Tulsa	
Kyle	Logie Hagen	University of Toronto	
Ahmad	Mayeli	University of Oklahoma	
Amanda	Morris	Oklahoma State University	
Nasir	Naqvi	Columbia University	
Kristina	Oldroyd	University of Utah	
Raquel	Phillips	Laureate Institute for Brain Research	
Tasha	Poppa	University of Southern California	
William	Potter	University of Tulsa	
Maria	Puhl	Laureate Institute for Brain Research	
Adam	Safron	Northwestern University	
Margaret	Sala	Southern Methodist University	
Jonathan	Savitz	Laureate Institute for Brain Research	
Heather	Saxon	University of Missouri	Dalton Cardiovascular Research Center
Will	Schoenhals	University of Tulsa	Laureate Institute for Brain Research
Colin	Stanwell-Smith	Floataway Inc.	
Adam	Teed	University of Texas at Dallas	
Yuri	Terasawa	Keio University	
Katie	Thompson	Laureate Institute for Brain Research	
Marisa	Toups	University of Texas Southwestern	
Satoshi	Umeda	Keio University	
Valerie	Upshaw	Laureate Institute for Brain Research	
Teresa	Victor	Laureate Institute for Brain Research	
Christina	Wierenga	University of California San Diego	
Colleen	Wohlrab	Laureate Institute for Brain Research	
Hung-wen	Yeh	Laureate Institute for Brain Research	
Adrian	Yoris	Favaloro University	
Fadel	Zeidan	Wake Forrest University	
Vadim	Zotev	Laureate Institute for Brain Research	
Nancy	Zucker	Duke University	